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Modeling and Analysis of a Reverse Supply Chain Network for Lead-Acid Battery Manufacturing

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Abstract

This paper describes the design of a closed-loop supply chain network for a lead-acid battery manufacturing operation. The planning model encompasses the entire closed-loop business process including purchasing, production, and end-of-life dead product collection and recycling. The model is a multi-objective, multi-echelon mixed integer linear program, which minimizes the total cost of the operations and the total pollution emissions related to transportation, subject to structural and functional constraints. Numerical examples have been provided to present the results regarding raw material procurement, production, recycling and inventory levels, and the transportation activities between the various echelons.

Keywords: *closed-loop supply chains; mixed integer programming; multi-objective mathematical modeling*

1. Introduction

In recent times, the supply chain management (SCM) concept has gained wide acceptance, and many studies have considered the problem of traditional supply chain design and modeling. Today, environmental concerns have increasingly underlined recycling and reuse as a means of pollution reduction, and have given importance to reverse logistics/closed-loop supply chains in both the academic and industrial world. Reverse logistics is defined as the process of planning, implementing and controlling the efficient, cost-effective flow of raw materials, in-process inventories, finished goods, and related information from the point of consumption to the point of origin for the purpose of recapturing value or proper disposal (Tibben-Lembke and Rogers, 2002).

Three important characteristics differentiate a reverse logistics system from a traditional supply chain system: 1) Most logistics systems are not equipped to handle product movement in a reverse channel; 2) Reverse distribution costs may be higher than those of moving the original product from the manufacturing site to the consumer; and 3) Returned goods often cannot be transported, stored, or handled in the same manner as in the forward channel. Compared to the forward logistics network, the reverse logistics flow may be quite different. When a customer returns an item to a retailer, the store collects the item to be sent to a centralized return center (CRC), and meanwhile, the information about the item and the condition of the returned product is recorded and entered into the system. In general, both the quantity and the quality of these returned products are uncertain.

There are mainly four reasons that lead companies to strategize their reverse supply chains. First, substantial long term economic gains can be derived from maintaining beneficial contacts with customers through customer service in addition to value added production recycling (Reddy, 2002).

Second, companies can reduce the "bullwhip effect" by using a reverse supply chain to get slow-moving products off the distribution networks and into recycling channels. In the traditional supply chain, it is assumed that consumers will buy all the products put in the distribution channel. When products are not moving, sales strategies such as markdowns and closeout sales are employed to entice customers. However, these sales practices send false demand signals up the supply chain. The reverse supply chain may isolate the traditional supply chain system from receiving false demand signals. The reverse supply chain could then move the products to other channels for profitable disposal.

The third reason is related to the concept of industrial ecology (Seuring, 2004). With the reverse supply chain, the business can exist within an extended supply chain of environmental and ecological resources, and waste and inefficiency in this eco-supply chain will be eliminated, just as economic waste must be eliminated in the narrower supply chain of business activities.

The last and the most important reason is that growing concerns for the environment have led to a range of new policies related to product-specific take-back obligations (Schultmann et al., 2006) for various industries in which the recovery of waste is an essential element. Producers will be responsible for collecting, sorting and recycling of discarded products at the end of their service life, a process known as extended product responsibility (EPR). Most of the North American manufacturers, especially the Original Equipment Manufacturers (OEMs) in the automotive sector and their part suppliers, have to comply with the EPR requirements in order to enter the European automobile market.

The present paper focuses on the development of an integrated model of a closed-loop supply chain network in the context of a lead-acid battery manufacturing operations, and is organized as follows. Section 2 briefly reviews the recent literature on reverse logistics. A description of the system under consideration is presented in Section 3, and the corresponding mathematical model is briefly outlined in Section 4. Section 5 presents a numerical example to demonstrate the application of the multi-objective model. Finally, the conclusions are summarized in Section 6.

2. Literature Review

This section presents a brief literature review of some of the modeling works on the distribution and recycling operation aspects of reverse supply chain networks. The reverse logistics network involves, on the one hand, the physical transportation of used products from the end users back to the producer(s), thus the distribution planning aspect; on the other hand, it involves the transformation of the returned products, by the producer(s), into usable products again, thus the recycling operation aspects.

2.1 Distribution Planning

A review of the quantitative models for reverse logistics from a modeling perspective is carried out by Fleischmann et al. (1997). Moreover, Fleischmann et al. (2000) and Fleischmann (2001) identified the general characteristics of logistics networks for product recovery in various industrial sectors, and developed quantitative models to support the design of such reverse logistics networks.

Barros et al. (1998) reported a case study on the design of a logistics network for recycling sand from the processing of construction waste in the Netherlands. The authors proposed a two-level capacitated facility location model, formulated as a mixed integer linear program.

Louwers et al. (1999) have considered the design of a recycling network for carpet waste with applications in both Europe and USA to determine appropriate facility locations and capacities for the regional recovery centers with the objective of minimizing investment, processing and transportation costs.

Shih (2001) employed a mixed integer programming model to design an optimal collection and recycling site selection plan for end-of-life computers and home appliances. The objective was to minimize the costs, which included the revenue from selling reclaimed material. The model was also used to evaluate various scenarios based on different take-back rates and operating conditions.

Krumwiede and Sheu (2002) developed a strategic decision-making model to guide the process of examining the feasibility of implementing reverse logistics in third-party (3PL) providers such as transportation companies. The model provided the structure, and the guidance needed, for the decision to expand the reverse logistics business.

Jayaraman et al. (2003) analyzed a reverse distribution network for an electronic equipment remanufacturing company in the U.S. The mixed integer programming model minimizes the reverse distribution costs and addresses a single-source plant with a restricted number of collection sites and refurbishing sites that could be opened.

Lim et al. (2005) addressed a reverse logistics network for product refurbishment involving electronic components using a multi-period and multi-objective mixed integer programming model to select the location of the collection centers. The objectives of the model were to maximize the net revenue, and minimize environmental impacts in terms of energy consumption and CO_2 emissions.

Kara et al. (2007) presented a reverse logistics network for white goods collection in Sydney, Australia, which establishes transfer stations, drop-off points, and a disassembly plant. They also developed a simulation model to examine the effects of various factors on the operations of the network.

Zhou et al. (2007) described the state of the battery recycling operations in China, and analyzed the possible obstacles to and weaknesses in the current practices in this field. Using a "soft system methodology", and with a view towards the best practices in effect in developed countries, they then proposed a practical approach to improve the collection, recycling, and recovery of batteries in China.

2.2 Closed-loop Supply Chain Networks

Krikke et al. (2001) developed a supply chain design entailing the production and return network for refrigerators. The modelling supports an optimal design structure of a product, i.e. modularity, repairability, recyclability, as well as the optimal locations and the allocation of material flows in the logistics system. The model is applied using real life R&D data of a Japanese consumer electronics company. The model is run for different scenarios using various parameter settings such as centralized versus decentralized logistics, alternative product designs, varying return quality and quantity, and potential environmental legislation based on producer responsibility.

Spengler (2002) developed an integrated operational-level decision support system for electronic scrap recycling companies in Germany. The multi-stage mixed integer linear programming model, which was based on linear activity analysis, maximized the total achievable marginal income subject to mass balance equations and capacity restriction for the recycling and dismantling of discard products.

Geyer and van Wassenhove (2003) developed a mathematical model of a closed-loop supply chain to explore the impact of constraints on the performance with respect to component reuse. They developed a mathematical model which maximizes the remanufacturing yield rate with constraints on limited component durability and finite product life cycles.

Schultmann et al. (2003) presented a hybrid approach to developing a closed-loop supply chain for spent batteries in the steelmaking industry. The approach combines an optimization model (essentially a capacitated two-level facility-location problem) for planning a reverse-supply network and a flow-sheeting process model that enables tailored simulations of various recycling options. The model determines the optimal location of the battery collection centers, and the optimal flows from the collection centers to sorting facilities, and from the sorting facilities to the recycling centers by minimizing the total fixed and transportation costs.

Beamon and Fernandes (2004) addressed a closed loop supply chain in which the plants produced new products and remanufactured used products. A multi-period integer programming model was introduced to determine which warehouses and collection centers should be open, centers should have sorting capabilities, and how much to ship between the sites.

Sheu et al. (2005) presented an optimization model to evaluate the integrated logistics operations of green-supply chain management (G-SCM) according to the Taiwan EPA regulations in 2003. The authors developed a linear multi-objective programming model to optimize the operations of both the integrated logistics and the corresponding used-product reverse logistics in a given chain of five layers.

What is discerned from the review of the literature in this area is that each supply chain has its own particular characteristics which impact the modeling process. Thus, the current paper proposes to develop a mathematical model of a closed loop supply chain for the lead-acid battery manufacturing operations. The model may be used to design the supply chain, or it may be used to analyze and optimize the operations of the chain once the design is completed.

3. System Description

The integrated closed-loop supply chain network model presented in this paper is based on the operations of a battery manufacturer located in North America. The company is a leading manufacturer of lead-acid batteries such as SLI (Starting, Lighting & Ignition) batteries, industrial batteries and stationary batteries. The company operates five manufacturing plants, one large on-site centralized warehouse, one recycling center (RC) and one on-site plastics molding plant. In addition to these facilities, the company also operates five regional distribution centers (DCs) distributing more than 4,000 different kinds of batteries to both the original equipment manufacturers (OEM) and the aftermarket (AM). The company has approximately 4,500 employees and net sales of $2.5 billion (U.S.) in the 2004 fiscal year.

The forward chain consists of the suppliers, the manufacturers, and the distribution centers which operate as the retail arm of the company; the reverse chain consists of the collection center (CC), and the recycling center; and the boundary between the two chains is, in this case, set at the interface between the collection centers (which is at the same location as the distribution centers) and the manufacturing plants, as shown in Figure 1.

Figure 1. The boundary between forward supply chain and reverse supply chain

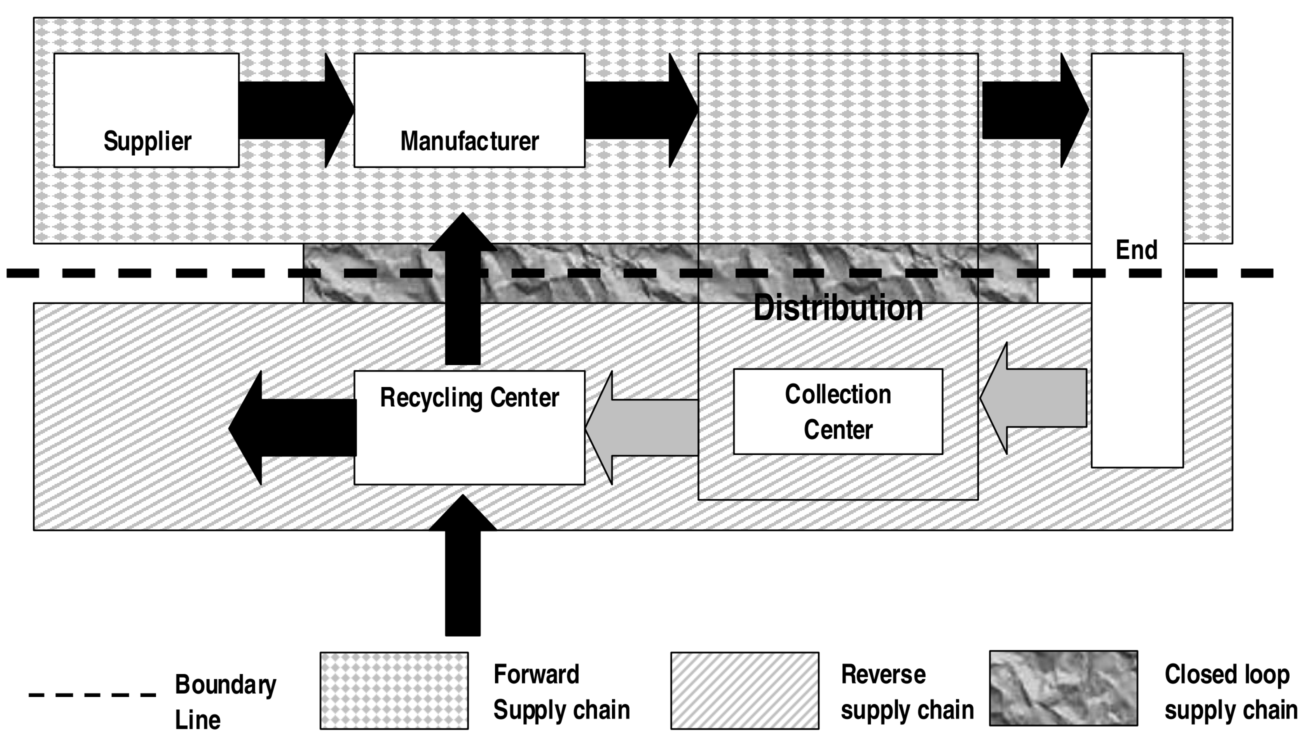
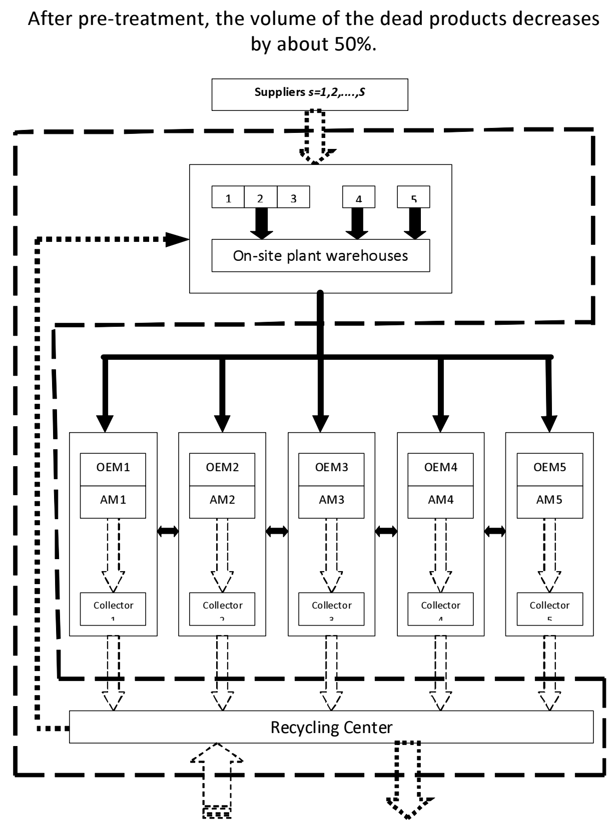


Figure 2. Material flow diagram



The lead-acid battery manufacturing industry has long been involved in recycling. A typical lead battery contains 18-20 pounds of lead, 11 pounds of sulfuric acid, and 3 pounds of plastic – all reclaimable, recyclable and reusable. Roughly 96 percent of the lead from recovered batteries is recycled, and the recycling of the plastic components is also increasing; thus the interest in reverse logistics.

The material flow diagram of the lead-acid battery manufacturing system is depicted in Figure 2. The batteries are manufactured based on expected customer demand, and kept at the centralized warehouse for later delivery to the regional distribution centers (through the company's own distribution network), and from there to the final customer demand points. At the end of their service lives, some portion (50%~70%) of the end-of-life dead batteries will be returned to the distribution centers through the dead product return and warranty return channels. At the distribution centers a percentage of the dead products may be pre-treated in order to separate the recyclable and non-recyclable components, the latter being sent to landfills. After pre-treatment, the volume of the dead products decreases by about 50%.

The on-site recycling center receives the dead products and processes them into recycled raw materials; the recycled raw materials, along with the virgin raw materials, enter the manufacturing operations to produce new batteries. The materials that cannot be recycled are sent to the landfill.

4. Mathematical Model

In this study, a generalized model has been developed that links the forward and reverse networks of a supply chain in the context of the battery manufacturing operations*. The model is an integrated multi-product, multi-echelon, multi-period planning tool which determines the material flow and the transportation routing for the network by optimizing two objective functions. The first objective function computes all the cost elements corresponding to each entity and activity within the network, and the second accounts for the pollution emissions associated with the transportation activities in the network. The constraints enforce capacity limits on production levels, inventories, and transportation activities in the network. Specifically, the following classes of constraints are in effect:

1. Production and inventory capacity restrictions at suppliers and plants
2. Distribution capacity restriction at plants and distribution centers
3. Processing and inventory capacity restrictions at recycling centers
4. Processing and inventory capacity restrictions at recycling centers
5. Transportation capacity available, in terms of weight and volume
6. Flow balance equations at various locations along the chain.

4.1 Assumptions

In the formulation of the model the following assumptions are considered:

1) Demand for various kinds of batteries is normally distributed with known mean and variance.

2) The entire product line is grouped into three product families based on their similarities in terms of their bill-of-material (BOM) requirements, manufacturing processes, production capacity requirements, etc. A product family may be produced at more than one manufacturing plant.
3) The planning period is 5 weeks due to the presence of seasonal and non-uniform demand patterns. The forecast loses its accuracy over longer periods.
4) Floor space presents a constrained inventory resource at the manufacturing plants, the distribution centers and the recycling center.
5) All in-transit transportation inventory costs are accounted for at the source (e.g., the cost of all the in-transit shipments from manufacturing plants to distribution centers are charged to manufacturing plants).
6) Safety stocks of raw materials (both virgin and recycled) and finished goods are computed using a centralized safety stock policy.
7) Manufacturing plants operate 8 hours a day, 5 days a week. Additional labour hours are acquired by hiring new labour, or using overtime.
8) The volume of the end-of-life products that are collected is calculated based on historical sales data multiplied by the take-back rate.
9) In addition to the end-of-life products collected at distribution centers, the recycling center purchases dead product sludge* from the secondary material market, which has already been pre-treated. These two sources of dead products are combined to provide input into the raw material recycling process.
10) The outgoing materials from the recovery process are assumed to be of the same grade as virgin raw material bought from the suppliers.
11) Logically and economically, a manufacturing plant chooses the raw material from the recycling center first, then the raw material from other suppliers; any surplus is sold to other industries.
12) During the recycling process, the materials which can not be recycled are disposed of, and the disposal costs are included in the recycling costs.
13) The lead time of the recycled raw material equals the lead time of the recycling process plus the lead time of transporting the recycled raw material from the recycling center to the manufacturing plant.

5. A numerical Example

The constraint-oriented transformation (or, the ε-constraint method) is used to convert the model into a single-objective optimization problem and to obtain the efficient points and the efficient frontier (Rardin, 2000). The frontier helps to characterize the range of the feasible solutions with respect to the (subjective) weights assigned to each objective.

The first objective function, i.e., the total costs, is chosen as the primary objective, and the second objective function, i.e., the total pollution emission index, is converted into a less-than-or-equal type constraint with the right-hand side specified as ε, and is added to the set of constraints. By selecting appropriate values for ε, different efficient solutions to the model are generated.

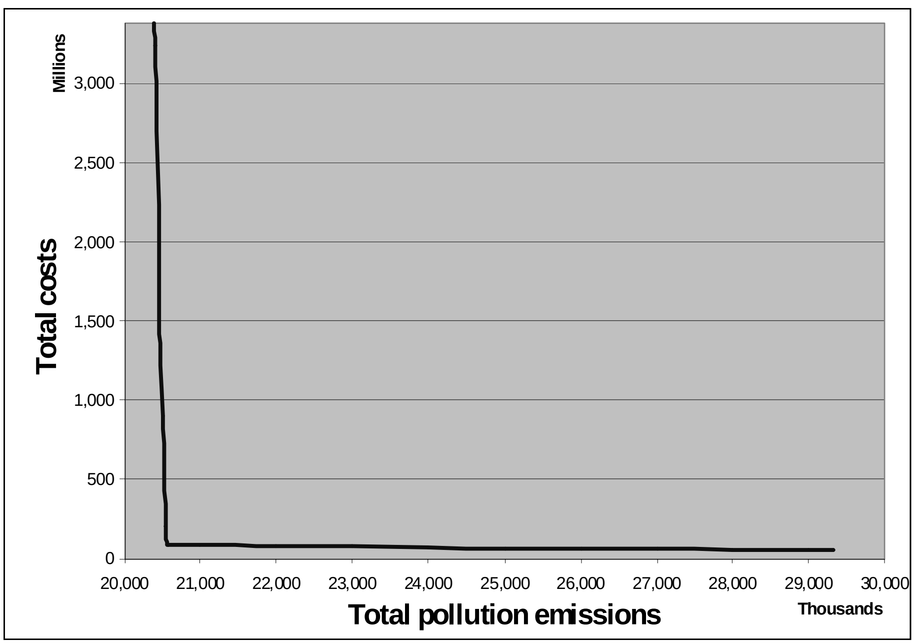
The model solutions for 20 different scenarios, each corresponding to a different ε value, are listed in Table 1, and displayed in Figure 3 in the form of an efficient frontier. In scenario 1, the model is solved as a simple optimization problem where only the second objective function is active, and the first objective function is ignored. The solution corresponds to a total cost of $3,382,317,000, and a total pollution emission index of 20,396,610 units. It represents an upper bound on the total cost, and a lower bound on the pollution index, respectively, and is identified by point B in Figure 3. Similarly, in scenario 20, the model is solved as a simple optimization problem with only the first objective function being optimized, while the second objective function is ignored. The solution corresponds to a total cost of $53,430,940, and a total pollution emission index of 29,326,830 units. It represents a lower bound on the total cost, and an upper bound on the pollution index, respectively, and is identified by point A in Figure 3. The other solution points in Figure 3 are obtained by initially setting ε = 29,326,830, and optimizing the first objective function' then reducing the ε value, and re-optimizing the first objective function, etc. As can be seen in Figure 3, the efficient solution C (corresponding to scenario #10 in Table 1) shows a reasonable balance between the two objective functions, and is chosen as the "best" feasible solution in this case.

* Battery sludge is originally collected from the replacement market, where the collectors drain ad shred the batteries. The sludge includes the following components: Plastics chips, lead sulfate ($PbSO_4$), lead Oxide (PbO) and lead metallic

Table 1. Model solution under various scenarios

Scenario	Objective Function 2 (Pollution index)	Objective Function 1 (Total cost, $)	Scenario	Objective Function 2 (Pollution index)	Objective Function 1 (Total cost, $)
1 **(point B)**	20,396,610	3,382,317,000	11	21,000,000	86,801,490
2	20,400,000	3,243,198,000	12	22,000,000	80,372,560
3	20,460,000	1,686,189,000	13	23,000,000	74,674,460
4	20,470,000	1,477,445,000	14	24,000,000	70,208,610
5	20,500,000	904,697,900	15	25,000,000	66,298,370
6	20,540,000	199,670,100	16	26,000,000	62,636,720
7	20,570,000	89,824,520	17	27,000,000	59,534,850
8	20,575,000	89,717,980	18	28,000,000	56,654,150
9	20,576,000	89,696,670	19	29,000,000	53,844,970
10 **(point C)**	20,579,000	89,646,440	20 **(point A)**	29,326,830	53,430,940

Figure 3. Efficient frontier for the planning model



The cost components corresponding to the efficient solution C are displayed in Figure 4 in descending order. As can be seen, the cost of transporting dead products from the collection centers to the recycling center accounts for a significant portion of the total costs (about 34%), followed by the labour cost (about 31%), the cost of pretreatment of dead products at collection centers (about 16.5%), the cost of collecting dead products (about 8%), and the virgin raw material cost (about 4.9%). It may also be concluded that the costs associated with the reverse part of the chain are much higher than those of the forward part of the chain, indicating that reverse logistics is "not necessarily a symmetric picture of forward distribution" (Fleischmann et al., 1997).

Figure 4. Cost components (in $M) corresponding to the efficient point C*

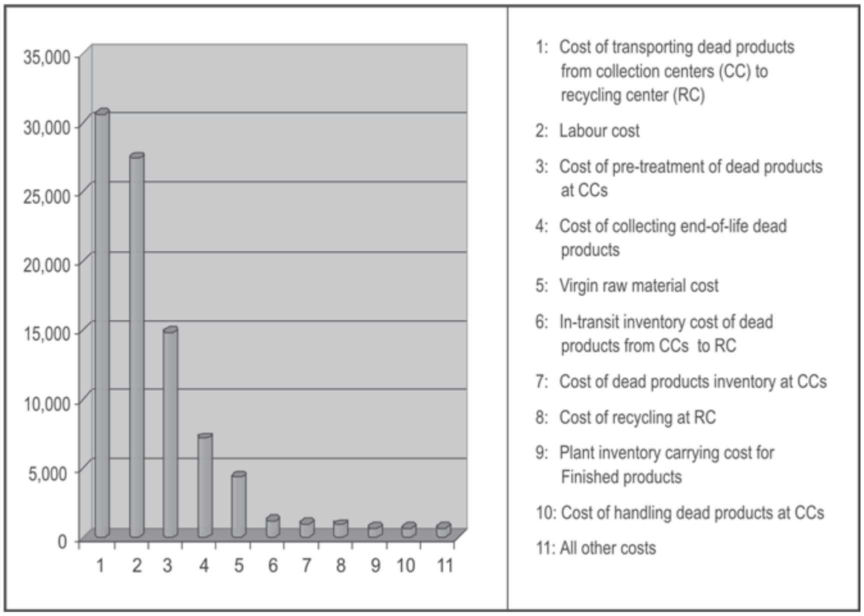


Table 2. Cost components (in $1000) corresponding to efficient solutions A, B and C

	Cost Component	Optimizing objective function 1 only (point A)	Optimizing objective function 1 only (point A)	Efficient solution (point C)
1	Virgin Raw Materials Cost	4,423	8,454	4,371
2	Virgin Raw Material Inventory Costs at Plants	2	4	2
3	Regular-Time and Over-Time Labour Hour Costs	27,480	27,799	27,480
4	Plant Inventory Carrying Cost for Finished Products	680	971	706
5	Inbound Transportation Cost of Products From Plants to DCs	86	71	78
6	In-Transit Inventory Cost of Products Between Plants and DCs	42	169	105
7	DC Inventory Carrying Cost	1	37	0
8	Handling Cost at DCs	0	0	0
9	Trans-shipment Cost of Products Between DCs	0	0	0
10	In-Transit Inventory Cost of Trans-shipments Between DCs	0	0	0
11	Cost of Collecting Dead Products	7,192	7,192	7,192
12	Cost of Dead Products Inventory at CCs	911	1,044	973
13	Cost of Handling Dead Products at CCs	653	653	653
14	Cost of Pretreatment of Dead Products at CCs	0	14,840	14,835
15	Cost of Transporting Dead Products from CCs to RCs	9,327	3,305,813	30,599
16	In-Transit Inventory Cost of Dead Products from CCs to RCs	1,153	1,566	1,195
17	Cost of Recycling at RC	970	8,229	955
18	Inventory Carrying Cost at RC	0	0	0
19	Cost of Handling Dead Products at RC	17	6	17
20	Cost of Buying Secondary Material Sludge	496	5,468	486
21	Income from Sale of Recycled Raw Materials	15	0	14
TOTAL COST (in $1000)		**53,431**	**3,382,317**	**89,646**

* Other costs include virgin raw material inventory costs at the plants, transportation cost of products from plants to DCs, in-transit inventory cost of products between plants and DCs, handling cost of dead products at the recycling center, cost of buying secondary material sludge

Table 3. Pollution emission index corresponding to efficient solutions A, B and C

Sources	At Point A	At Point B	At Point C
Due to transportation from plants to DCs	373,490	310,286	339,431
Due to transportation from DCs to RCs	28,953,340	20,086,320	20,239,569
Total Pollution Emissions (units)	**29,326,830**	**20,396,610**	**20,579,000**

Table 4. Pollution emission index corresponding to efficient solutions A, B and C

Sources	i = 1	i = 2	i = 3	i = 4	i = 5	i = 6	i = 7
Virgin raw material	0	30,921	1,087	23	0	1,087	23
Recycled raw material used	67,846	0	0	0	7,115	0	0
Total recycled raw materialavailable from the recycling center	**110,809**	**0**	**0**	**0**	**7,642**	**0**	**0**

Table 5. Amount of raw materials (in lbs) used in plants p=1,…,5 in periods t=1,…,5

Plan, *p*	Period, *t*	Raw Material						
		i = 1	i = 2	i = 3	i = 4	i = 5	i = 6	i = 7
1	1	7,502	4,638	129	1	518	129	1
	2	123	25	2	2	10	2	2
	3	123	25	2	2	10	2	2
	4	123	25	2	2	10	2	2
	5	123	25	2	2	10	2	2
2	1	8,366	4,475	139	0	741	139	0
	2	3,154	1,213	49	0	388	49	0
	3	3,154	1,213	49	0	388	49	0
	4	3,154	1,213	49	0	388	49	0
	5	3,154	1,213	49	0	388	49	0
3	1	8,635	4,882	145	0	705	145	0
	2	2,570	988	40	0	316	40	0
	3	2,570	988	40	0	316	40	0
	4	2,570	988	40	0	316	40	0
	5	2,570	988	40	0	316	40	0
4	1	6,255	2,926	100	0	651	100	0
	2	2,935	1,129	45	0	361	45	0
	3	2,935	1,129	45	0	361	45	0
	4	2,935	1,129	45	0	361	45	0
	5	2,935	1,129	45	0	361	45	0
5	1	1,204	430	18	2	140	18	2
	2	189	38	3	3	15	3	3
	3	189	38	3	3	15	3	3
	4	189	38	3	3	15	3	3
	5	189	38	3	3	15	3	3

* The raw materials are, respectively, lead, sulfuric acid, antimony, arsenic, polypropylene, calcium, and tin

Table 2 displays the various cost components corresponding to the efficient solutions A, B and C, while Table 3 summarizes the corresponding pollution emission indices associated with these three points.

The production plan corresponding to the efficient solution C is described below. Table 4 shows the amount of raw material used in the production processes at the manufacturing plants. For example, it is noted that 67,846 units of raw material i=1 are used in the production of the product families, and that they are all recycled from the dead products. On the other hand, the 1,087 units of raw material i=3 used in the production processes are all virgin raw material. Any surplus recycled raw material is made available for sale on the market. Table 5 represents the number of units of raw material used in the production process at each plant during the planning period, and Table 6 shows the amount of recycled raw material shipped from the recycling center to each plant during the planning period. For example, in the first period, 18,401 units of raw material i=1 were shipped to plant p=1 from the recycling center.

Table 7 displays, for each part family, the aggregated demand, the number of units produced, and the safety stock levels held during the planning period. For example, the total production of product family q=1 (at all the plants) is 996,596 units, of which 969,563 units (or, 97%) are delivered to the distribution centers to satisfy customer demands, and 6,207 units are kept at the plant warehouses as safety stock; the remaining 24,826 units are passed on as initial inventory for the next planning period.

The details of the aggregated production and the safety stock levels depicted in Table 7 are given in Tables 8 and 9; table 8 defines the production level of each product family at each manufacturing plant in each of the five weeks during the production plan; and table 9 specifies the safety stock levels of each product family at each plant over the planning period, indicating that in this case the safety stock level is the same from week to week.

Table 5. Amount of raw materials (in lbs) used in plants p=1,…,5 in periods t=1,…,5

Recycling Center, *r*	Plan, *p*	Period, *t*	Raw Material						
			i = 1	i = 2	i = 3	i = 4	i = 5	i = 6	i = 7
		1	18,401	0	0	0	1,197	0	0
		2	123	0	0	0	0	0	0
	1	3	123	0	0	0	0	0	0
		4	123	0	0	0	0	0	0
		5	123	0	0	0	0	0	0
		1	21,963	0	0	0	1,695	0	0
		2	3,154	0	0	0	388	0	0
	2	3	3,154	0	0	0	388	0	0
		4	3,154	0	0	0	393	0	0
		5	3,154	0	0	0	384	0	0
		1	19,664	0	0	0	2,054	0	0
		2	2,570	0	0	0	215	0	0
1	3	3	2,570	0	0	0	215	0	0
		4	2,570	0	0	0	211	0	0
		5	2,570	0	0	0	0	0	0
		1	12,893	0	0	0	0	0	0
		2	2,935	0	0	0	0	0	0
	4	3	2,935	0	0	0	0	0	0
		4	2,935	0	0	0	0	0	0
		5	2,935	0	0	0	220	0	0
		1	2,004	0	0	0	221	0	0
		2	189	0	0	0	15	0	0
	5	3	189	0	0	0	15	0	0
		4	189	0	0	0	15	0	0
		5	189	0	0	0	15	0	0

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Table 7. Aggregated demand, production, and safety stock levels

Finished Goods	Product Family		
	q=3	q=3	q=3
Finished goods produced at the plants during the planning period	996,596	211,382	2,864
Finished goods stored at plant warehouses as safety stock	6,207	2,600	51
Aggregated customer demand	965,563	198,381	2,613

Table 8. Units of product families q=1,…,3 manufactured at plants p=1,…,5 in periods t=1,…,5

Product Family, *q*	Plan, *p*	Week				
		t=1	t=2	t=3	t=4	t=5
1	1	273,575	0	0	0	0
	2	0	0	0	0	0
	3	1,255	3,489	3,489	3,489	3,489
	4	195,404	0	0	0	0
	5	99,468	103,234	103,234	103,234	103,234
2	1	0	0	0	0	0
	2	70,593	0	0	0	0
	3	19,304	24,489	24,489	24,489	24,489
	4	0	0	0	0	0
	5	23,529	0	0	0	0
3	1	658	477	477	477	477
	2	0	0	0	0	0
	3	0	0	0	0	0
	4	166	0	0	0	0
	5	25	27	27	27	27

Table 9. Safety stock of product families q=1,…,3 at manufacturing

Product Family, *q*	Plants				
	p=1	p=2	p=3	p=4	p=5
1	2,143	1,531	1,899	633	0
2	0	779	520	1,039	263
3	10	0	0	0	40

Table 10. Relevant data for the reverse part of the supply chain

End-of-life products	Product Family		
	q=3	q=3	q=3
Aggregated forecast of dead products collected during planning period	671,453	308,512	6,269
Number of units of end-of-life batteries transported to recycling center	324	0	0
Number of units of pretreated end-of-life batteries transported to recycling center	671,129	190,706	0
Inventory of end-of-life batteries in time period t=5	0	117,806	6,269

As far as the reverse part of the supply chain is concerned, the collection centers collect the dead products, and transport them to the recycling center to be processed into recycled raw material. Table 10 displays the relevant data. For product family q=1 for example, 671,453 units of end-of-life dead batteries come into the collection centers; 671,129 units (almost 99%) are pretreated and only 324 units are left untreated. They are subsequently shipped to the recycling center. No inventory of this product family is kept at the collection centers. For product family q=2, however, 308,512 units of end-of-life dead batteries are collected, 190,706 units (or, 62%) are subsequently pretreated and shipped to the recycling center, and the remaining 117,806 units (or, 38%) are kept at the collection centers as inventory.

Finally, Tables 11 and 12 show, respectively, the amount of pretreated and non-pretreated dead products shipped from the collection centers to the recycling center. For instance, in week 4, there are 17,845 pretreated units of product family q=1 that are shipped to the recycling center using the transportation mode k=3 (Table 11), whereas there are only 324 units of this product family that are shipped, using the same transportation mode, without pretreatment (Table 12).

6. Conclusions

In this paper a model for a reverse supply chain network has been developed in the context of the lead-acid battery manufacturing industry. The model determines a closed-loop supply chain design (by connecting the forward supply chain to the point where the end-of-life dead products enter the reverse logistics chain), while minimizing the total cost as well as the effects of pollution emissions during transportation as a secondary objective. The model is a decision making tool for determining the levels of raw material consumption (both virgin as well as recycled) , production, inventory, and workforce at different points along the chain, as well as for determining the patterns of product shipments and the transportation mode selection between the various entities in the system.

The model is solved using the commercial solver LINGO 9.0 (LINDO Systems, 2003), and the solutions prove the computational feasibility of the model with the å-constraint method. A typical run of the model in its present form (involving 10,280 constraints and 22,396 variables—including 125 binary variables) reaches the optimum solution in about 3 minutes of CPU time.

Table 11. Units of pretreated dead products shipped from distribution centers (DCs) to the recycling center using transportation mode k*

Recycling Center r	Transport Mode k	Period t	Distribution centers														
			DC 1			DC 1			DC 1			DC 1			DC 1		
			Product Families, q			Product Families, q			Product Families, q			Product Families, q			Product Families, q		
			q 1	q 2	q 3	q 1	q 2	q 3	q 1	q 2	q 3	q 1	q 2	q 3	q 1	q 2	q 3
1	1	1	7,240	0	0	4,931	0	0	0	0	0	0	0	0	7,478	0	0
		2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	2	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	3	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		3	14,722	0	0	4,443	0	0	2,686	0	0	17,874	0	0	0	0	0
		4	17,845	0	0	5,385	0	0	3,256	0	0	21,664	0	0	0	0	0
		5	16,745	0	0	4,333	0	0	1,807	0	0	20,329	0	0	0	0	0

* Available transportation modes are: 1=Regular Truck, 2=Expedited Truck, 3=Rail.

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Table 12. Units of non-pretreated dead products shipped from distribution centers (DCs) to the recycling

Recycling Center r	Transport Mode k	Period t	Distribution centers														
			DC 1			DC 1			DC 1			DC 1			DC 1		
			Product Families, q			Product Families, q			Product Families, q			Product Families, q			Product Families, q		
			q 1	q 2	q 3	q 1	q 2	q 3	q 1	q 2	q 3	q 1	q 2	q 3	q 1	q 2	q 3
1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	2	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	3	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		4	324	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

* Available transportation modes are: 1=Regular Truck, 2=Expedited Truck, 3=Rail.

As a multi-objective optimization model, the solutions provide a range of alternatives representing various trade-offs between the two objectives of total costs and total transportation pollution emissions. The ultimate choice of the solution is up to the decision-maker.

The model is generalized enough to be relevant as a planning tool for the reconfiguration of supply chain networks in most types of OEMs or manufacturing operations involving hazardous material. The model may easily be adapted to different scenarios by adding/removing any relevant constraints or objective functions.

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